

**MINIATURIZATION OF THE FLOWING FLUID ELECTRIC CONDUCTIVITY  
LOGGING TECHNIQUE**

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1 **ABSTRACT**

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An understanding of both the hydraulic properties of the aquifer and the depth distribution of salts is critical for evaluating the potential of groundwater for conjunctive water use and for maintaining suitable groundwater quality in agricultural regions where groundwater is used extensively for irrigation and drinking water. The electrical conductivity profiles recorded in a well using the flowing fluid electric conductivity logging (FEC logging) method can be analyzed to estimate interval specific hydraulic conductivity and estimates of the salinity concentration with depth. However, irrigation wells that are common in agricultural regions have limited access into them because these wells are still in operation, and the traditional equipment used for FEC logging cannot fit through the small access pipe intersecting the well. A modified, miniaturized FEC logging technique was developed such that this logging method could be used in wells with limited access. In addition, a new method for injecting water over the entire screened interval of the well was developed to reduce the time required to perform FEC logging. Results of FEC logging using the new methodology and miniaturized system in two irrigation wells are also summarized.

17 **INTRODUCTION**

18

19 In regions where the salinity of the groundwater varies considerably with depth, such as the  
20 Central Valley of California, an understanding of both the hydraulic properties of the aquifer and  
21 the depth distribution of salts is critical for evaluating the potential of aquifers for conjunctive  
22 water use. Groundwater is also used extensively for irrigation in agricultural regions and  
23 maintaining suitable groundwater quality levels is becoming an increasing concern. The  
24 electrical conductivity (EC) profiles recorded in a well using the flowing fluid electric  
25 conductivity logging (FEC logging) method can be analyzed to estimate interval specific  
26 hydraulic conductivity and estimates of the salinity concentration with depth (e.g., Tsang and  
27 Doughty, 2003; Doughty and Tsang, 2005).

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29 As described by Tsang and Doughty (2003), the flowing FEC logging method involves first  
30 replacing the wellbore water by de-ionized water or water of a constant salinity distinctly  
31 different from that of the formation water. This is done by injecting de-ionized water down a  
32 tube to the bottom of the well, while simultaneously pumping from the top of the well, until the  
33 EC of the water pumped out of the well stabilizes at a low value. Next, the pumps are turned off  
34 and the well is pumped only from the top at a constant low flow rate, while an electrical  
35 conductivity probe is lowered into the borehole to record the EC as a function of depth and time.

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37 Although the FEC logging method has been successfully conducted over the past 15 years (e.g.,  
38 Tsang et al, 1990; Kelly et al., 1991; Pedler et al., 1992; Bauer and LoCoco, 1996; Doughty et  
39 al., 2005), the method has generally only been conducted in easily-accessible vertical wells with  
40 diameters ranging between 5 to 15 cm. These studies were performed on wells that were not  
41 actively producing water with permanently installed well pumps and motors. Existing irrigation  
42 wells can provide valuable information on aquifer properties and the vertical salinity distribution.  
43 A drawback of using existing wells is that the accessibility into them is limited because the well  
44 pumping equipment blocks access to traditional probes used for FEC logging. Access into these  
45 wells can only be achieved through a 3.8 cm diameter metal pipe intersecting the well at  
46 approximately a 45° angle (Figure 1). The restricted access also limits the size of piping used to  
47 inject water for FEC logging. The diameter of irrigation well casing encountered during this

48 study was large, typically around 46 cm, so the traditional method of injecting water at a single  
49 point to replace the water in the casing was not practical with a small diameter injection pipe.

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51 Devising a method where FEC logging can be used in irrigation wells with limited access and  
52 large diameters is important since there are thousands of wells in agricultural regions that could  
53 potentially be logged to enhance the understanding of the hydrogeology of these regions. To  
54 facilitate logging these wells, a modified and miniaturized FEC logging technique was developed  
55 and tested in irrigation wells located in the San Joaquin Valley, the southern portion of the  
56 Central Valley of California. This technical note describes novel methodology and equipment for  
57 performing FEC logging on actively-pumped irrigation wells with limited accessibility.

## 58 59 **METHODS**

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61 The probes typically used to perform FEC logging have a 3.8 cm diameter and have an inflexible  
62 1.0 - 2.0 m long section. A probe of this size would not fit into most well access pipes and could  
63 not bend around the lip where the well casing and access pipe intersect. For our study, a small  
64 electrical conductivity probe manufactured by Campbell Scientific (Logan, UT) was used that  
65 had a cross-sectional area of 2.5 x 1.9 cm and was 8.9 cm long. We attached to the probe five  
66 stainless steel weights that had a 2.5 cm diameter and were 5.0 cm long to reduce the buoyancy  
67 of the probe. The probe depth was measured using a depth encoder, which is a device that detects  
68 depth measurements and converts them to electrical signals for input into data acquisition  
69 systems.

70  
71 During traditional FEC logging, constant salinity water with salinity lower than the existing  
72 wellbore water is injected at the bottom of the well screen simultaneously as the wellbore water  
73 is extracted from the top of the wellbore. The less dense, lower salinity water should  
74 theoretically move up the wellbore as it displaces the existing water. In an unconsolidated  
75 formation, some of the injected water is likely to enter the formation over time, with more water  
76 entering the bottom of the formation where the water is injected. Injection of water into the  
77 irrigation wells with limited access is a challenge since the small diameter access pipe (3.8 cm)  
78 limits the diameter of tubing that can be used in the well. In addition, both the injection and

79 extraction hose must simultaneously fit through the pipe opening. FEC logging is typically  
80 performed in wells with diameters in range from 6 - 15 cm. The diameter of the irrigation well  
81 casing used in this study is nearly 46 cm, so it would take a long time to replace the borehole  
82 water using tubing with a small diameter and a single injection point.

83

84 Because replacing the existing well water using a small diameter tube is difficult in these large  
85 diameter wells with limited access, we developed a new technique of injecting water using  
86 tubing with emitters to provide nearly uniform injection over the length of the well screen.  
87 Emitters were originally developed for drip irrigation in agricultural fields, but they have not  
88 been used to inject water into wells. Because of the pressure drop along the length of the tubing,  
89 pressure-compensating emitters were used to provide a uniform injection rate. The emitters were  
90 inserted into 1.9 cm diameter reinforced PVC tubing every 0.3 m over a length of 24 m  
91 beginning at the bottom of the hose. Above the 24 m interval, the emitters were spaced at 0.6 m  
92 intervals for a total of nearly 39 m of hose with emitters. The total length of the hose was around  
93 90 m. The emitters are rated at 12.5 L/hr for pressures between 10-50 psi, and we verified that  
94 the flow rate remained nearly constant as the pressure changed. The emitters maintain a constant  
95 flow rate with a flexible membrane that becomes compressed as the pressure increases. A  
96 constant flow rate is maintained because the permeability of the membrane decreases with  
97 increasing pressure. Our new injection method reduces the time of well water replacement  
98 compared to the traditional, single point injection method since the injection occurs over the  
99 screened interval and mixes with the existing water over that interval. The existing well water  
100 does not have to be entirely replaced as with the single point injection method because FEC  
101 logging still works as long as the low salinity water becomes well-mixed with the existing well  
102 water and the resulting water salinity has enough contrast with the formation EC.

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104 During the water-replacement part of our well logging tests, constant salinity water with an  
105 electrical conductivity between 0 - 500 mS/cm was injected into the wellbore via emitters while  
106 the wellbore water was simultaneously extracted from the top. Centrifugal pumps were used to  
107 inject and extract water, and the extraction and injection hose had a 1.9 cm diameter. A  
108 schematic of our experimental set-up is shown in Figure 1. The results of two tests are presented  
109 in this paper. In the first test, the extracted well water was run through de-ionizing filters, and the

110 de-ionized water was then subsequently reinjected into the well. In the second test, water for  
111 injection was supplied from a water truck containing water with a conductivity of 500 mS/cm.  
112 After the wellbore water was replaced by the de-ionized or constant salinity water, the electrical  
113 conductivity (EC) in the well was recorded over time as the water was extracted from the top of  
114 the well at a constant rate.

115

## 116 **RESULTS**

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118 This section presents the results of two tests conducted in irrigation wells in the Central Valley of  
119 California (near Los Banos, CA). The goal of these tests was to demonstrate that the modified,  
120 miniaturized logging system we developed could be used to conduct FEC logging in the large-  
121 diameter irrigation wells. One test was conducted in an abandoned irrigation well that was open  
122 at the top because the pump and motor housing had been removed and the other one was  
123 conducted in a well with limited access. A small borehole camera was sent down the well to  
124 measure the water table, screened intervals, and well depth. Analysis of the FEC profiles  
125 presented in this section will be conducted in future work to determine the location, inflow rate,  
126 and salinity of the inflow points.

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### 128 *FEC Logging in an Open Irrigation Well*

129

130 The modified FEC technique and equipment were tested in an open irrigation well with screens  
131 that began at 37 m below ground surface and continued to the bottom of the well which was  
132 approximately at 68 m. The water table in this well was around 8 m below ground surface. De-  
133 ionizing filters were used to reduce the salinity of the well water that was extracted. The water  
134 extracted from a depth of 9 m was run through the filters and then the de-ionized water was  
135 injected into the well via emitters distributed over a depth range of 29 to 68 m. The water was  
136 extracted/injected at a rate of 13.6 L/min over a period of 5 hours. Because this was an open  
137 well, we were able to send the EC probe into the well while both hoses were in it to monitor the  
138 change in EC over time as the de-ionized water was injected. After about an hour, we began to  
139 observe a decrease in the EC over the entire screened interval and the EC continued to decrease  
140 over time, indicating that the method of injecting water using the small diameter tubing with the

141 emitters was effective in this large diameter well. The EC across the diameter of the well was  
142 measured at a particular depth and only small variations in the EC were measured indicating that  
143 the de-ionized water had become well-mixed with the existing well water.

144  
145 After a five hour period of replacing the wellbore water, the injection pump was shut off and  
146 only the extraction pump was on at a rate of 18.9 L/min, and the EC profile in the well was  
147 logged for the next 3 hours. Figure 2 presents the initial EC profile in the well before water was  
148 extracted/injected and the subsequent hourly EC profiles after the water replacement had ceased  
149 and water was only extracted. Over the screened interval, the initial EC profile is nearly uniform  
150 at 1.35 mS/cm except for a peak near the top of the well screen between 37 to 40 m. After  
151 injecting the de-ionized water, the EC decreases to around 0.6 mS/cm between 50 and 67 m and  
152 then increases to 0.95 mS/cm between 43 and 50 m. The peak present in the initial profile was  
153 still there after the de-ionized water was injected, indicating that flow into the well at that  
154 location is higher than in the rest of the well. The peak observed at the top of the well screen  
155 propagates up the wellbore over time. Below a depth of 43 m, the FEC profile propagates  
156 downward with time most likely because of buoyancy flow.

157  
158 *FEC Logging in a Limited Access Irrigation Well*

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160 The miniaturized FEC logging method was also tested in an irrigation well with limited access.  
161 The screens in this well began at 35 m and continued to the bottom of the well which was  
162 approximately at 48.5 m. In some of the irrigation wells, including the well we logged, a layer of  
163 oil was present above the water. The oil is used for lubricating the pump motor and drive shaft,  
164 but the excess oil drips into the well and accumulates on the surface of the water. In this well, the  
165 top of the oil layer began about 2.3 m below the top of the access pipe intersecting the well. The  
166 bottom of the oil layer (which corresponds to the top of the water column) was located around  
167 3.2 m below the access pipe, giving an oil layer that was 0.9 m thick. In order to keep the inside  
168 of the conductivity probe where the electrodes are located from contacting the oil layer while the  
169 probe was lowered into the well, the openings to the electrodes on the probe were temporarily  
170 sealed using foam earplugs and a string was attached to the earplugs to pull them off once the  
171 probe got past the oil layer. We verified that the oil did not enter into the probe while it was

172 lowered through the oil layer by monitoring the electrical conductivity, which remained around  
173 zero until the earplugs were removed.

174

175 We successfully inserted both the injection and extraction tubing through the small access pipe.  
176 Water was injected at 22.8 L/min via emitters at depths of 19.5 to 48.5 m and extracted at 16.7  
177 L/min from a depth of 5 m and the pumps were left on for 4 hours. Because the injection water  
178 for this test was supplied from a water truck, we were able to inject water at a slightly higher rate  
179 than it was extracted to ensure that the formation water was not pulled into the well. In a well  
180 with limited access, the EC probe cannot fit through the access pipe if the extraction and  
181 injection hose are both already in the well. Therefore, the injection tubing was removed from the  
182 well after the pumps were shut off so that the EC probe could be lowered into the well. The EC  
183 profile was logged immediately after the lower salinity water had been injected. The extraction  
184 pump was turned back on at a rate of 11.4 L/min once the initial log was completed. The initial  
185 EC profile before the well water was replaced was not logged for this particular well.

186

187 Figure 3 presents the FEC logs at different times. The initial log after replacement of the well  
188 water was fairly uniform over the screened interval and had an average EC of 0.95 mS/cm. The  
189 small-scale variability in the EC measurements was because of interference with the reel motor  
190 and the EC probe which was later corrected by modifying the datalogger program. The EC  
191 profile was measured hourly and revealed that the EC increased faster towards the bottom of the  
192 well compared to the top of the screened interval. This indicates that the formation at the bottom  
193 of the screened interval is more permeable or the EC of the water at the bottom of the well is  
194 higher. The observed change in EC over time also demonstrates that the water replacement  
195 method was successful in lowering the EC of the water in the wellbore enough to provide  
196 contrast with the formation EC.

197

## 198 **SUMMARY**

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200 These results presented in this note demonstrate that the miniaturized logging system and new  
201 method of injecting water can be successfully used to conduct FEC logging in irrigation wells  
202 with large diameters and limited access. The use of tubing with emitters reduces the time needed

203 to replace the wellbore water over the screened interval of larger diameter irrigation wells, and  
204 the equipment required for the logging is easily transportable and can be developed at a  
205 relatively low cost. The miniaturization of the logging equipment and the new method of  
206 dispersing water over the well screen also allows hydrogeology studies to be performed on an  
207 increased number of existing wells which reduces the need to expend funds on other methods of  
208 accessing irrigation wells (e.g. temporarily removing the pump motors) or installing new  
209 monitoring wells. An additional use for this method could be for wells with obstructions in  
210 slightly off-vertical casing or bends in small-diameter well casing caused by improper  
211 installation. A long inflexible probe cannot always move around obstructions and bends whereas  
212 the probe/weight configuration used in our study would increase the accessibility into these  
213 wells. The miniaturized logging system is a powerful tool for obtaining information on water  
214 quality and aquifer properties that would otherwise not be possible for wells that have limited  
215 accessibility.

216

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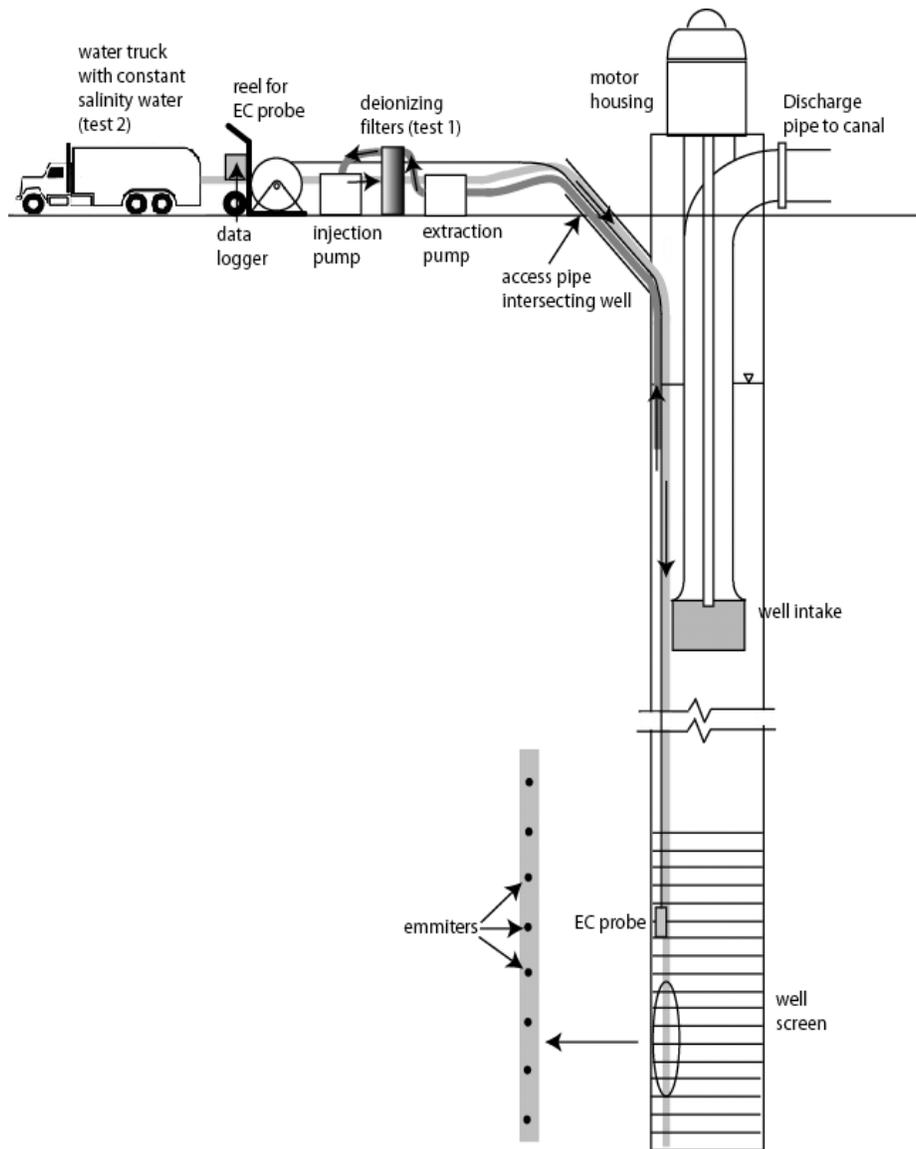
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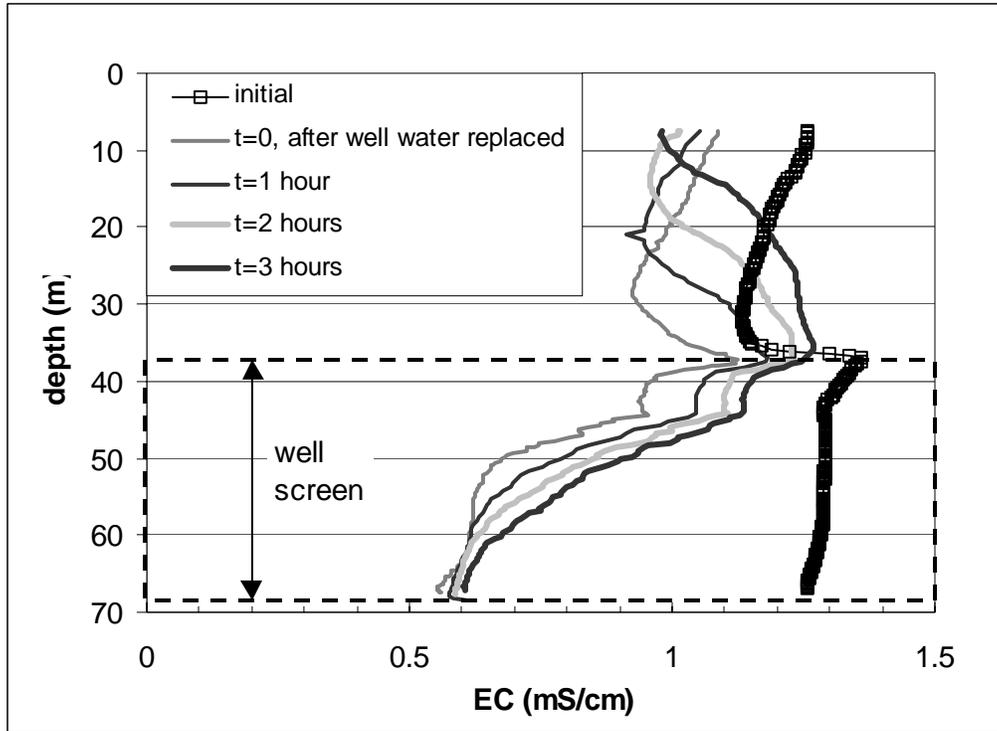
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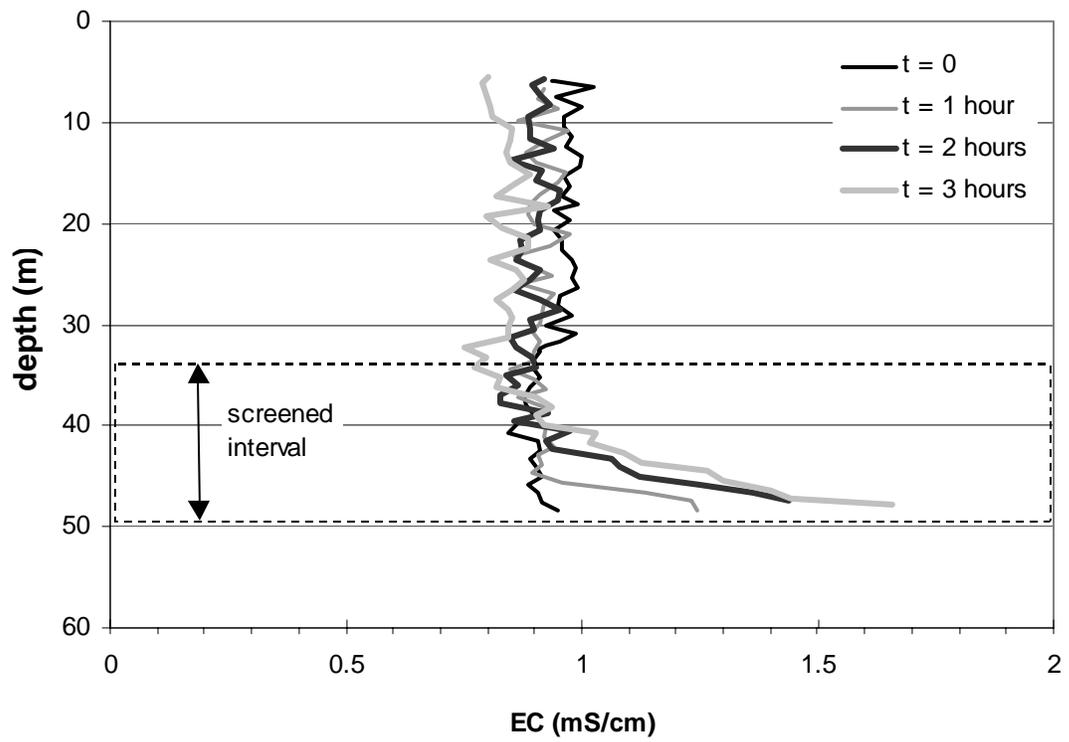
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**Figure 1.** Schematic of the modified FEC logging apparatus for a large-diameter irrigation well with limited access (not to scale).



**Figure 2.** FEC profile prior to water replacement and hourly profiles after the well water had been replaced in an open well.



**Figure 3.** Hourly FEC profiles after the well water had been replaced in a well with limited access.